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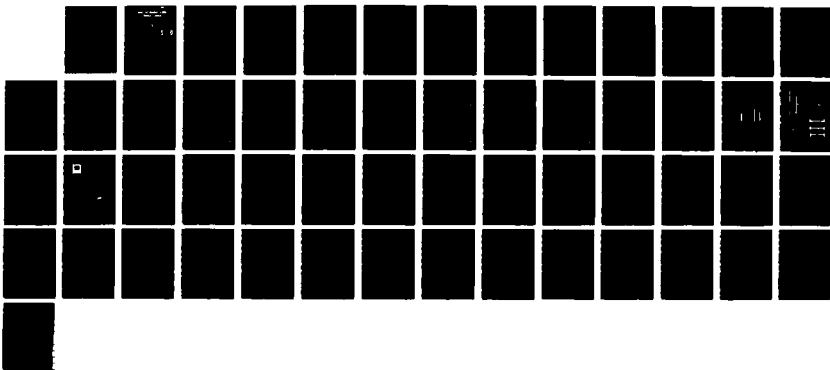
THE EFFECTS OF TORQUE RESPONSE AND TIME DELAY ON  
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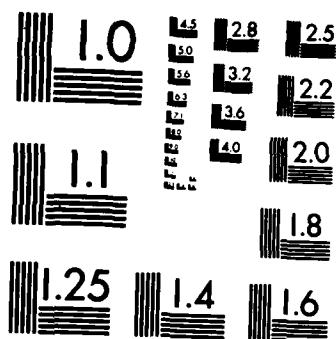
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# NAVAL POSTGRADUATE SCHOOL Monterey, California



## THESIS

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THE EFFECTS OF TORQUE RESPONSE AND TIME  
DELAY ON ROTORCRAFT VERTICAL AXIS  
HANDLING QUALITIES

by

Peter Allen Fyles

December 1987

Thesis Advisor:

Richard M. Howard

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The Effects of Torque Response and Time Delay  
on Rotorcraft Vertical Axis Handling Qualities

by

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Lieutenant, United States Navy  
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Submitted in partial fulfillment of the  
requirements for the degree of

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from the


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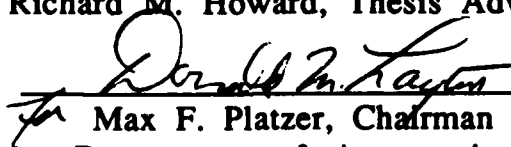


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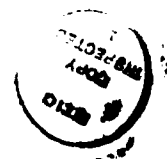
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## I. INTRODUCTION

The current version of the U.S. military helicopter handling qualities specification, MIL-H-8501A (Ref. 1), is a 1961 revision of a 1952 document. The purpose of the MIL-H-8501A is to provide the requirements for the flying and ground handling qualities of military rotorcraft. The MIL-H-8501A is issued as a mandatory requirement guideline to all manufactures, procurers, and operators of military rotorcraft. The characteristics which are defined in the MIL-H-8501A specify the minimum necessary design criteria to provide satisfactory handling qualities.

The MIL-H-8501A gave excellent guidance for rotorcraft design and flight testing until the late 1960's. Since then new technology in the helicopter industry has forced much of the specification to become inadequate or outdated. The MIL-H-8501A does not address several critical areas such as instrument meteorological conditions (IMC), system failures, flight envelopes, etc. In addition the MIL-H-8501A does not account for the new demanding tasks required of modern military helicopter missions. An attempt was made to revise the MIL-H-8501A in 1968 but the revision was never adopted due to a lack of well-conditioned data (Ref. 2).

The V/STOL handling-qualities specification, MIL-F-83300 (Ref. 3), was published in 1970. It attempted to include rotorcraft and was accepted by the U.S. Air Force, but the U.S. Navy and U.S. Army perceived the specification as having too many shortcomings and rejected it.

Although rotorcraft and V/STOL aircraft may both operate in the hover and low-speed flight regime, there are notable differences in thrust generation and thrust management. Thrust response of jet VTOL aircraft is a direct function of throttle position and can be modeled by a simple lag followed by a first-order response. In contrast, the thrust response of an rpm-governed helicopter is a complex function of blade incidence, inflow damping and rotor-speed response which is dependent upon rotor inertia, transmission characteristics, and engine-governor dynamics.

A joint Army/Navy program has been formed to update the handling qualities specifications for military rotorcraft, the results of which will be a new proposed specification. To aid in this project the U.S. Army Aeroflightdynamics Directorate at the NASA Ames Research Center has been tasked with investigating effects of torque response and time delay on rotorcraft vertical axis handling qualities. The study described in this thesis was carried out in conjunction with the larger research program at NASA Ames. The portion of this research which involves investigation of time delay is included in the Appendix.

## II. PREVIOUS RESEARCH

The thrust response of an rpm-governed helicopter due to a collective step input is characterized in Figure 1. "RPM-governed" means that the engine fuel control system (vice the pilot) makes the necessary power corrections in the attempt to maintain a constant rotor speed. The amount of excess thrust is dependent on the amount of maximum available thrust.

The "bucket" in Figure 1 is the difference between the theoretical thrust response curve (constant rotor speed, dashed line) and the actual thrust response curve (solid line). The shape of the initial "bucket" is directly proportional to rotor inertia and engine-governor response. For a small helicopter with a relatively light rotor system the bucket would be deep; the rpm of the light blades would be heavily influenced by any minor change in torque. In contrast, a helicopter with a heavy rotor system would be better able to resist sudden changes in torque. The large blades would be able to absorb the torque fluctuations and therefore have a smaller rpm drop.

Engine-governor response determines how quickly the thrust recovers from the "bucket". A fast engine-governor would enable the thrust to climb back to the theoretical constant rotor speed curve much sooner than a slow engine-governor. The mechanics of the engine fuel control and fuel sensing components determines how fast or slow an engine governor is.

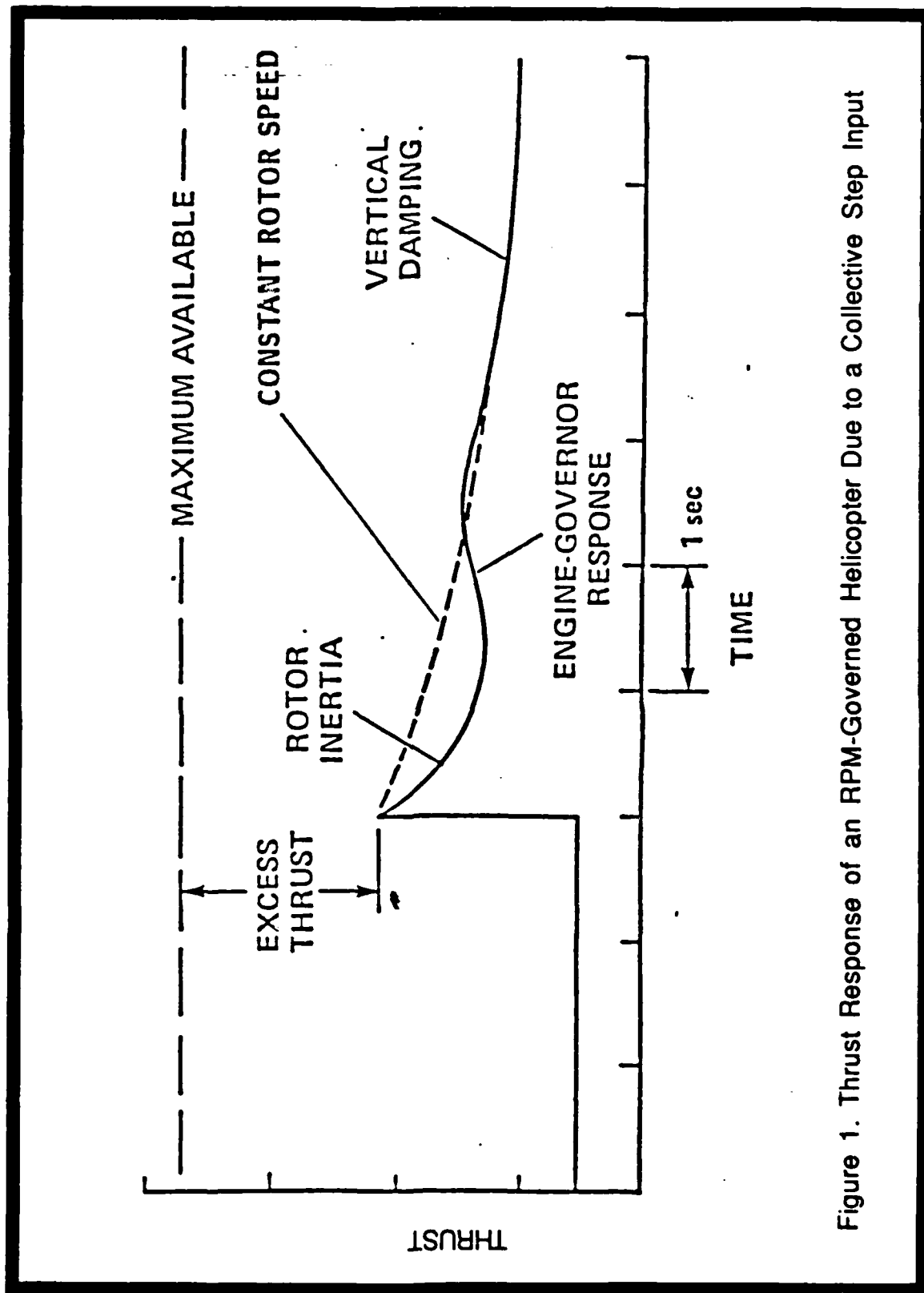


Figure 1. Thrust Response of an RPM-Governed Helicopter Due to a Collective Step Input

The influence of vertical damping determines the shape of the constant rotor speed curve. Vertical damping ( $Z_w$ ) is a characteristic of motion which determines how responsive an aircraft is to movement in the vertical axis. The units of vertical damping are  $\text{sec}^{-1}$ . Each type of aircraft has its own particular vertical damping value. If the magnitude of the vertical damping value is too small the vertical response of the aircraft will be too abrupt, unpredictable, and subject to pilot induced oscillations. If the magnitude of the vertical damping value is too large the vertical response will be sluggish. A large vertical damping coefficient causes the thrust to decrease much faster than a small damping coefficient (Figure 1).

Corliss and Blanken (Ref. 4) studied the effects of handling qualities due to engine governor response time, excess thrust, rotor inertia, rpm control, and height damping for specific nap-of-the-Earth maneuvers. Results of these simulations showed a direct effect of engine-governor response and rotor inertia on rotorcraft handling qualities. They found that decreases in engine-governor response time can significantly degrade the handling qualities rating and that increasing the rotor inertia will have a minor but desirable effect.

Although normal rotorcraft vertical damping values are approximately  $-.3 \text{ sec}^{-1}$ , in-flight experiments of rotorcraft height response by Hindson at the Ames Research Center (Ref. 5) and the Canadian National Aeronautical Establishment (NAE) (Ref. 6) revealed that vertical damping values between  $-.3 \text{ sec}^{-1}$  and  $-.05 \text{ sec}^{-1}$  are acceptable if enough excess power is available.

In the past, several in-flight and ground simulations have researched the parameter of thrust/weight ratio (T/W). Utilizing the NASA CH-47 variable-stability helicopter, Kelly showed that the T/W ratio is highly dependent upon the evaluation task (Ref. 7). He found that for aggressive tasks, such as takeoff and landing, the minimum T/W for satisfactory flying qualities was 1.09; but for less aggressive tasks, such as the approach alone, a T/W of 1.03 could be acceptable provided the vertical damping ( $Z_w$ ) was greater than  $-.25 \text{ sec}^{-1}$ . As shown in Figure 1, rotorcraft thrust is time-varying and difficult to measure. Blanken (Ref. 8) suggests: "A more conventional and perhaps less controversial approach is to consider excess power in the form of maximum vertical steady rate of climb ( $h_{\max}$ ). One way to simulate different values of  $h_{\max}$  of a helicopter during a investigation is to limit the transmission torque to values less than the torque capability of the engine." In researching the demanding "bob-up" maneuver Blanken (Ref. 8) concluded that the helicopter must have some minimum value of  $h_{\max}$  in order to achieve desired performance. If given sufficient time, the pilot can obtain the desired performance with marginal  $h_{\max}$ . He also concluded that for each configuration there is a certain time limit below which the pilot ratings begin to degrade.

In October of 1986 the NRC of Canada attempted to address the problem of how to characterize the vertical axis handling qualities of rotorcraft (Ref. 6). Limited in-flight research by the NRC variable stability helicopter produced five separate data runs of varying



vertical rate response. Figure 2 shows the five data runs and the five variables investigated. Runs 1 and 5 received excellent pilot ratings and runs 2, 3 and 4 received poor ratings. At first this was puzzling because runs 1 and 4 had very similar vertical rate responses but drastically different pilot ratings. It was then observed that the two runs that received the high marks had very similar torque responses. As a result of their analysis the NRC has suggested that rotor torque response be further investigated as a testable requirement of rotorcraft handling qualities. Rotor torque is easy to measure and would take into account all of the complicated, hard to measure parameters which are "downstream" of it. The pilot's only indication of torque is what is represented on the gauge; therefore there is a need to understand the relationship between displayed rotor torque dynamics, mission tasks, and pilot opinion ratings. This study will report the relationship between these variables.

Pilot opinion ratings for this study were based upon the Cooper-Harper (Figure 3) rating scale. NASA TN-D-5153 (Ref. 10) defines handling qualities as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role". For this simulation and military operations in general, handling qualities are specified in terms of levels. Cooper-Harper ratings of 1-3.5 refer to Level 1, ratings of 3.5-6.5 refer to Level 2, and ratings of 6.5-8.5 refer to Level 3. Level 1 handling qualities are considered adequate

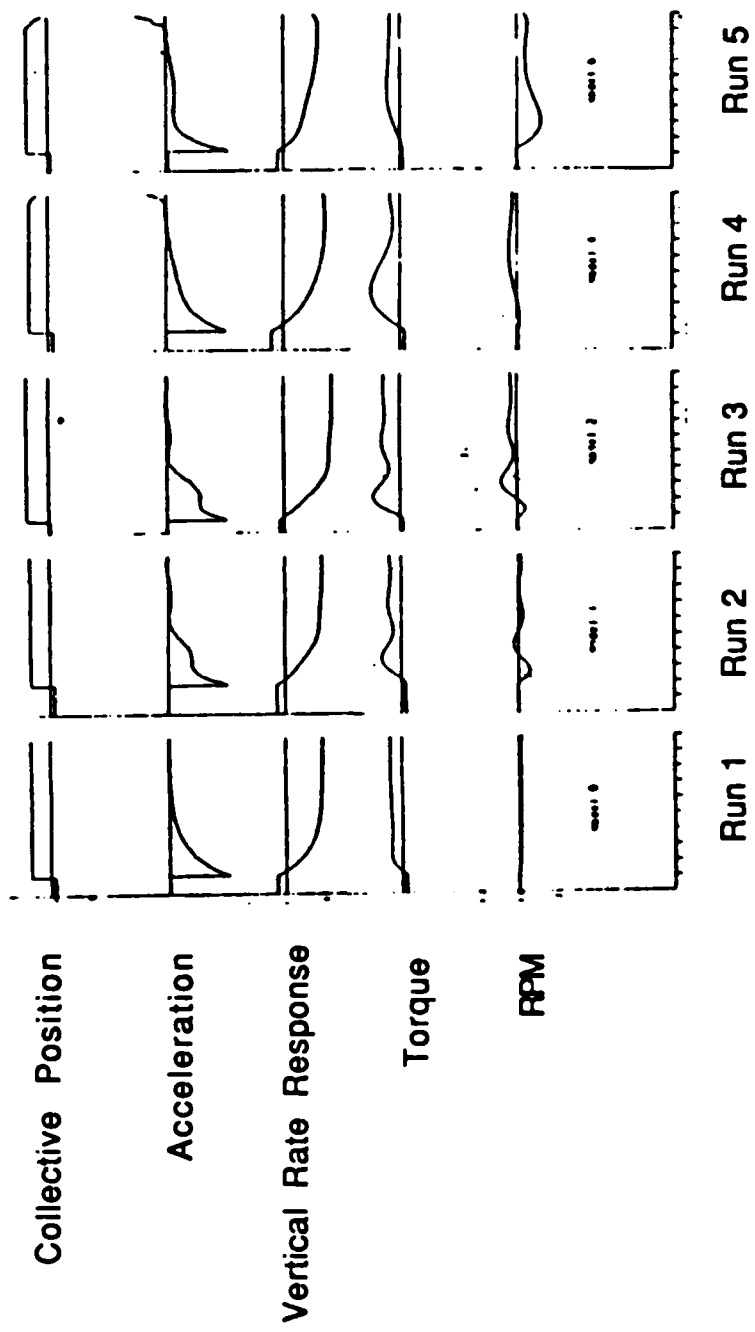


Figure 2. NRC Canada Time Response Data (Ref. 6)

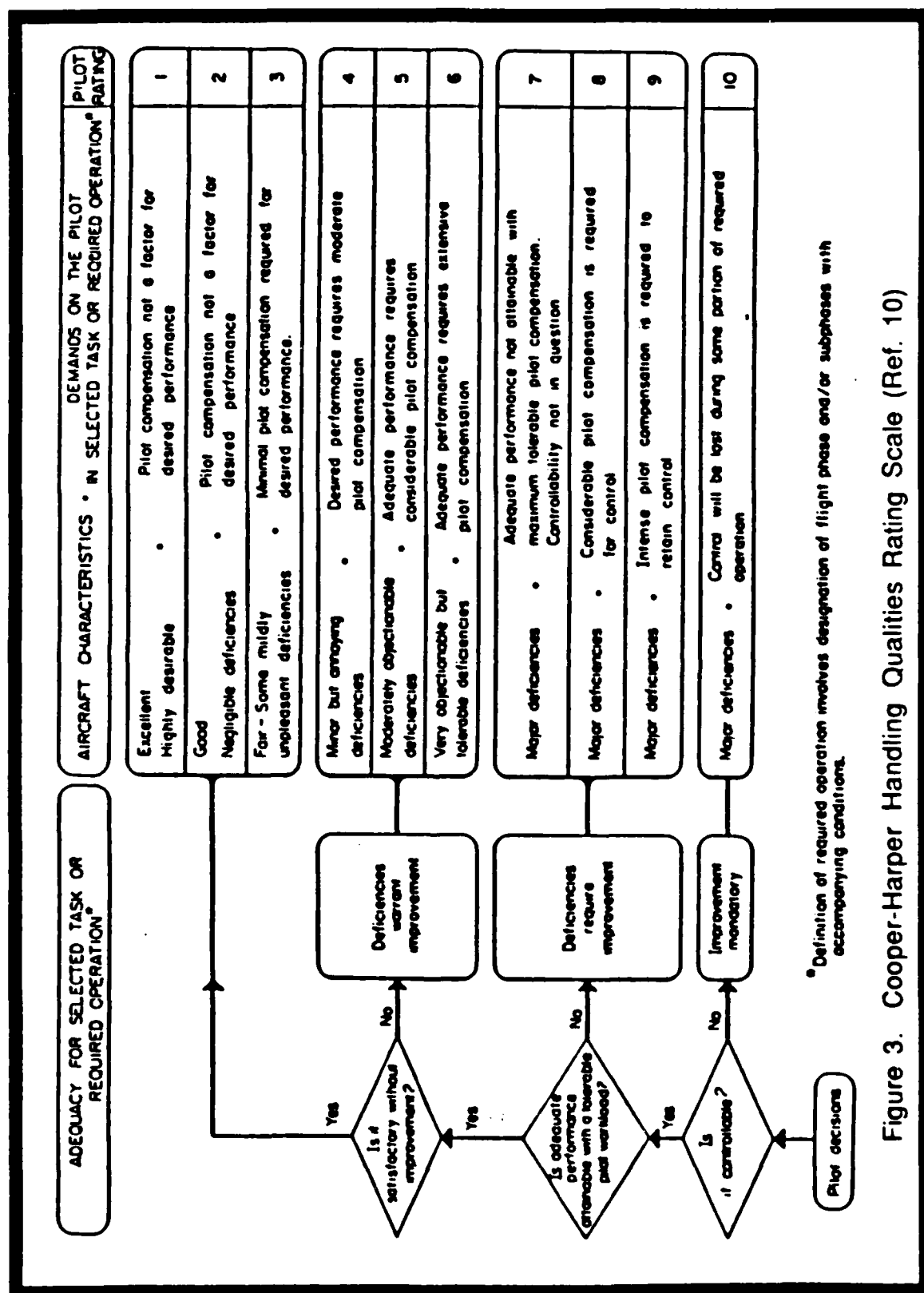


Figure 3. Cooper-Harper Handling Qualities Rating Scale (Ref. 10)

to complete the mission task. Level 2 handling qualities are adequate to complete the task but there is an increase in pilot workload and/or a degradation in mission effectiveness. Level 3 handling qualities mean that aircraft can be controlled safely but pilot workload is excessive and/or mission effectiveness is inadequate.

### III. EXPERIMENTAL SET-UP

#### A. OVERVIEW

The main objective of this experiment was to collect supporting data for the torque dynamic response requirements and to analyze the effects of the vertical damping and time delay. The experiment was actually divided into two separate experiments: the simulation and the in-flight testing. The simulator was primary used to analyze effects of torque response on rotorcraft handling qualities. The NASA-Army variable-stability CH-47B helicopter was utilized to study the effects of time delay and vertical damping.

#### B. THE SIMULATION

The study was conducted at the NASA-Ames Flight Simulation Facility. The "R" ICAB simulator (Interchangeable Cab, Rotorcraft version) was used for the cockpit, controls and displays. Motion was not considered a critical factor; therefore the ICAB was mounted fixed base. Figure 4 shows a schematic of the height response model used in the simulation.

##### 1. Rotorcraft Model

The computer model was run using a CDC 7600 Mainframe as the host computer. The rotorcraft model used in this simulation was ARMCOP (Ref. 9). ARMCOP is a ten-degree-of-freedom, nonlinear mathematical model. The ARMCOP model was configured to simulate a Bell 249 Model Helicopter (four-bladed Cobra). Although there are

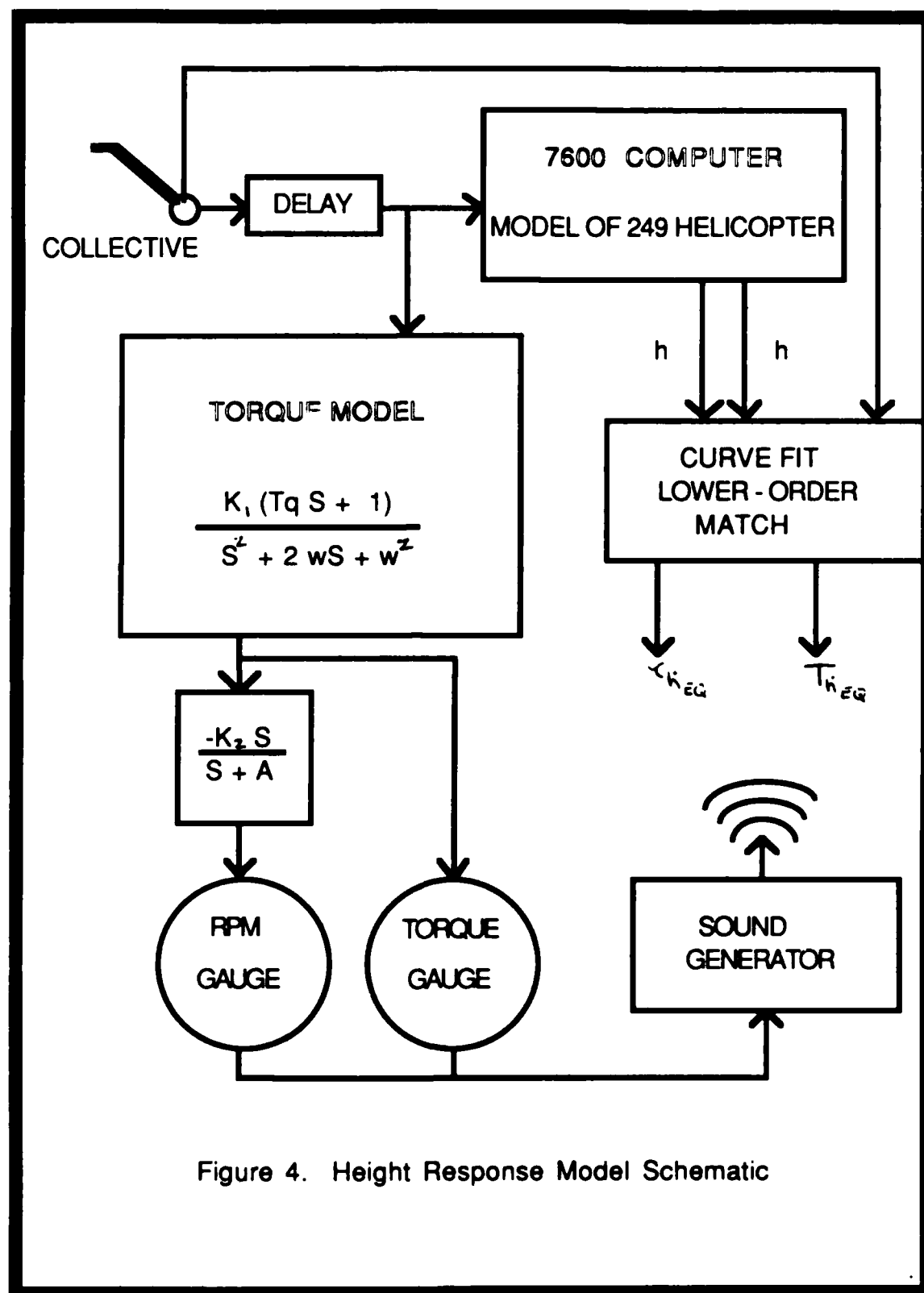
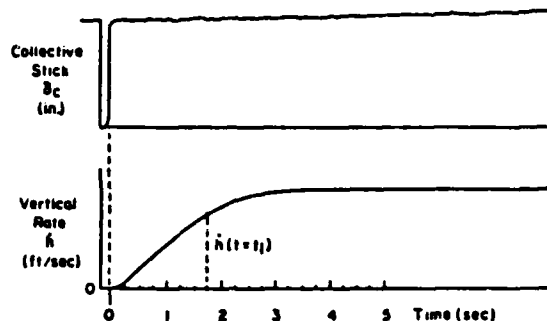


Figure 4. Height Response Model Schematic

only two four-bladed Cobra helicopters in the world, this model configuration was chosen because of its superb record of in-flight validation, especially in the hover (less than 15 knots) and the low speed (less than 45 knots) flight regimes. To insure that the vertical response was independent of the height above the ground the ground effect model was removed. The model contained a stability and augmentation system (SCAS) which consisted of an attitude command system. A heading-rate command system was utilized in the yaw axis. The collective axis controller commanded altitude rate. In the attitude mode the steady-state forces could be cancelled by the use of trim buttons. In order to maximize the fidelity of the simulation and reduce adverse influences on the pilot ratings, the control forces were adjusted to represent an actual helicopter as closely as possible. It was required to optimize the artificial control forces to minimize the effects on pilot ratings. The simulator was flown extensively to insure the maneuverability limits and the proper functioning of the desired control responses were met.

## 2. Lower Order Curve Fit

The proposed 8501 update places a requirement that the vertical rate response following a collective step input will have a first-order appearance. In order to comply with this requirement a lower order curve-fitting program was utilized in this simulation. The equations and procedures used in the curve-fitting program are shown in Figure 5. By the use of a low-order curve-fit program it



- Obtain  $\dot{h}$  readings (ft/s or m/s) from  $\dot{h}$  response to step collective input at .03 sec intervals for a time span of 0-5 sec (see sketch above) - a total of 101 data points.
- Use a three variable nonlinear least squares algorithm to obtain a best fit curve to this data in the time domain using the following form for the estimated  $\dot{h}$  ( $\dot{h}_{est}$ ).

$$\dot{h}_{est}(t) = K \left[ 1 - e^{-\frac{1}{T_{h_{eq}}} (t - \tau_{h_{eq}})} \right] \text{ for } t > 0$$

where  $t$  is time (sec) and  $K$ ,  $\frac{1}{T_{h_{eq}}}$  and  $\tau_{h_{eq}}$  are the variables.

- The function to be minimized is the sum of squares of the error ( $e$ ), defined as,

$$e^2 = \sum_{i=1}^{101} [\dot{h}(t - t_i) - \dot{h}_{est}(t - t_i)]^2$$

where  $t_i$  is the time (sec) at the  $i^{th}$  observed data point (see sketch)

- The goodness of fit of the estimated curve is determined by the coefficient of determination ( $r^2$ ) which is defined as,

$$r^2 = \frac{\sum_{i=1}^{101} [\dot{h}_{est}(t - t_i) - \bar{\dot{h}}]^2}{\sum_{i=1}^{101} [\dot{h}(t - t_i) - \bar{\dot{h}}]^2}$$

where  $\bar{\dot{h}}$  is the mean of the observed  $\dot{h}$ ,

$$\bar{\dot{h}} = \frac{\sum_{i=1}^{101} \dot{h}(t - t_i)}{101}$$

Figure 5. Height Response Curve-Fitting Procedures (Ref. 11)



was possible to determine the equivalent time delay and vertical damping.

### 3. Torque Model

The torque response transfer function shown in Figure 4 was first developed for the Canadian experiments. In order to correlate our data as closely as possible the same transfer function was used in this simulation. Three variables of the torque model were investigated: the time constant ( $T_q$ ), damping ratio ( $\xi$ ), and frequency ( $\omega$ ). By a study of the Canadian results it was possible to determine broad ranges from which to alter the three variables. For this simulation the time constant ( $T_q$ ) varied from 0 to 4 sec, damping ( $\xi$ ) from .1 to 1, and the frequency ( $\omega$ ) from .25 to 10 rad/sec. By varying these parameters it was possible to change the overshoot, damping and frequency of the torque gauge response. RPM readouts were possible by adding another transfer function to the output of the torque model. To simulate the noise environment in flight, a noise generator was connected to the output of the torque and RPM gauges. Noises produced for the experiment included rotor and engine noise which varied with collective input.

### 4. Displays

A four-window, wide-field-of-view, high resolution, computer generated image (CGI) was displayed to the pilot. The computer-generated imagery was generated using the Singer-Link Digital

Image Generator (DIG) computer. The flight gauge information was processed by a PDP 11/55 computer and displayed on CRT. Previous experiments identified the lack of sufficient depth perception cues to be a significant shortcoming. Depth perception cues were especially important in this simulation to enable the task to be performed at low flight altitudes. A head-up display (HUD), like that shown in Figure 6, was installed in the cockpit. One element of the HUD was a tape display and digital readout of the torque. Standard instruments were also generated on the HUD and drawn on a CRT. The standard instrument panel included the following flight instruments:

- 1) airspeed indicator
- 2) altimeter
- 3) vertical speed indicator
- 4) turn and slip indicator
- 5) attitude indicator
- 6) radio magnetic indicator

The head-up and panel-mounted displays were generated on an Evans and Sutherland Picture System One (PSI) computer.

## 5. Visual References

A computer-drawn image of the hovering visual reference (HOVR) boards was used. The HOVR boards were attached to the hover test-rig towers as shown in Figure 7. A detailed diagram of the HOVR boards is illustrated in Figure 7. The geometry of the parallax board (Figure 8) created precise vertical cues. When the

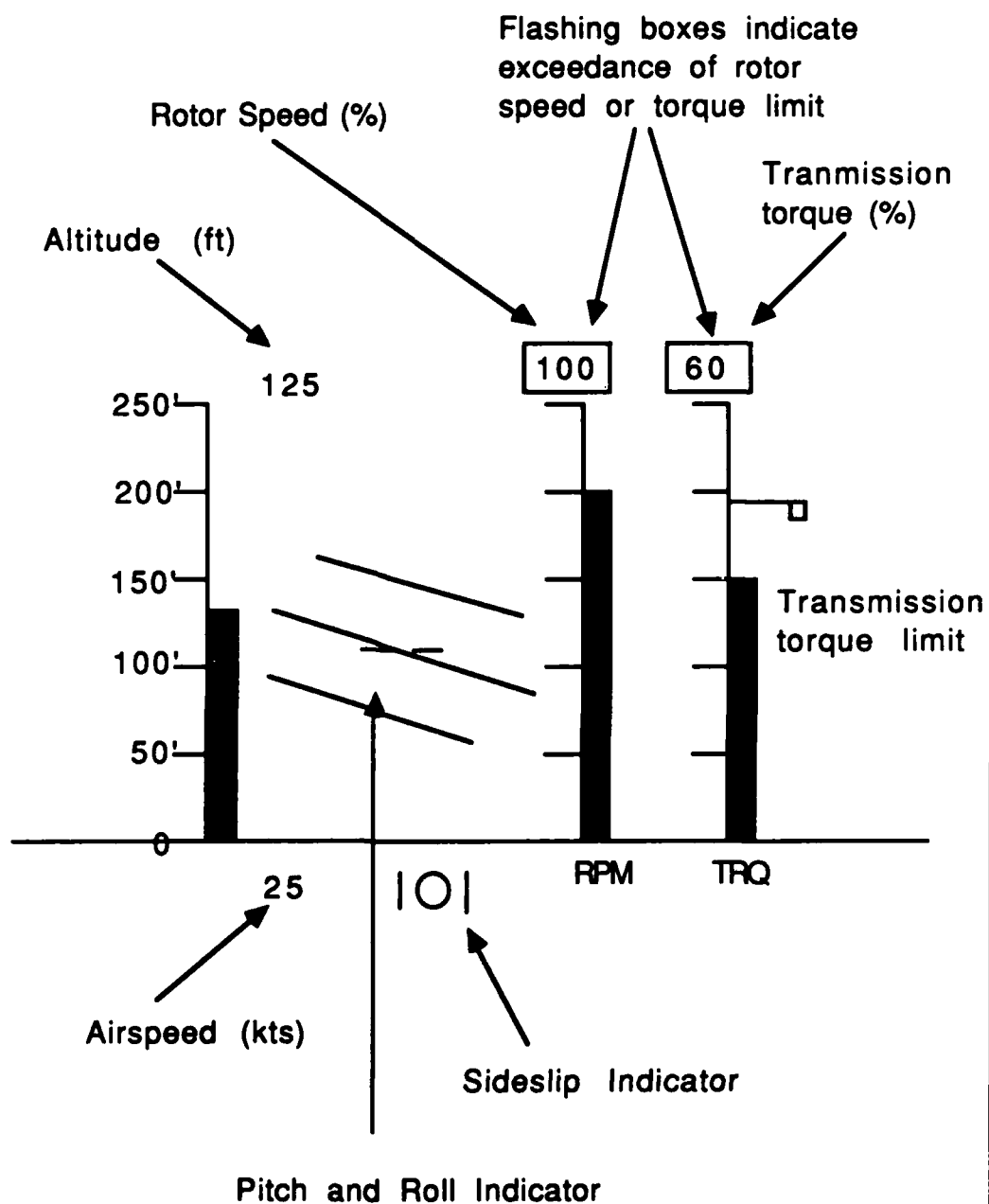


Figure 6. Head up display

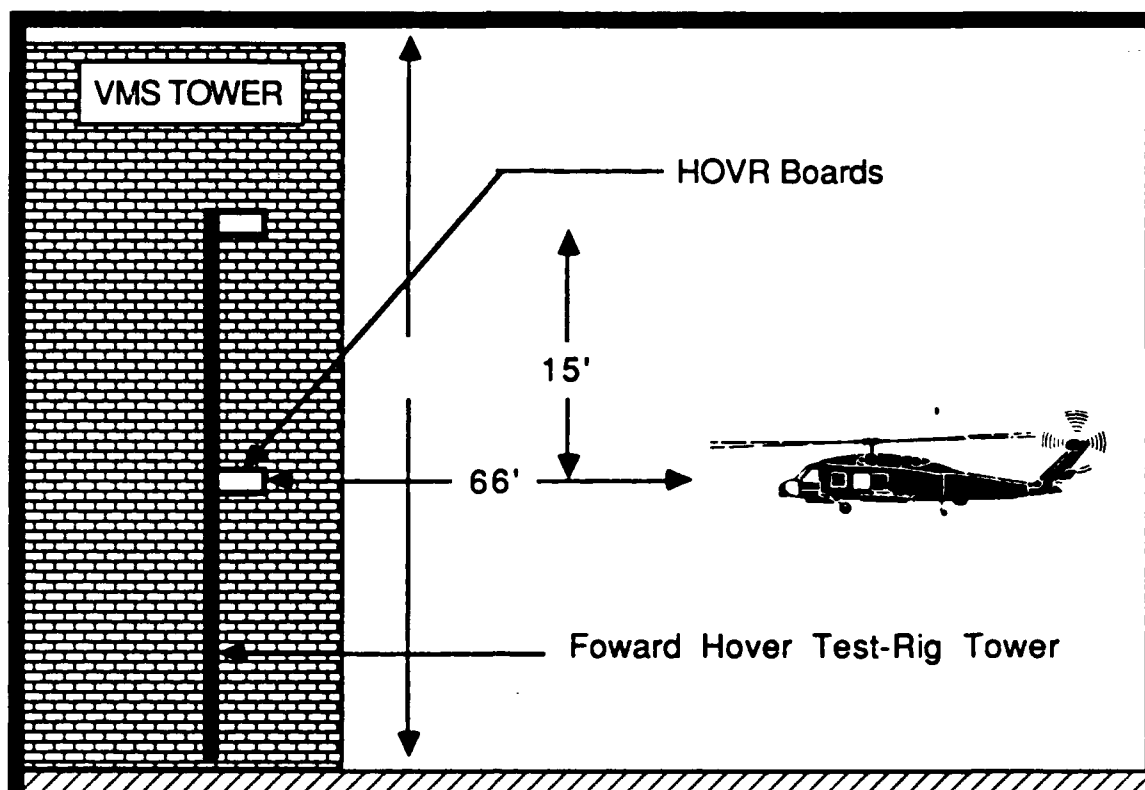


Figure 7. Hover Test-Rig and Vertical Motion Tower

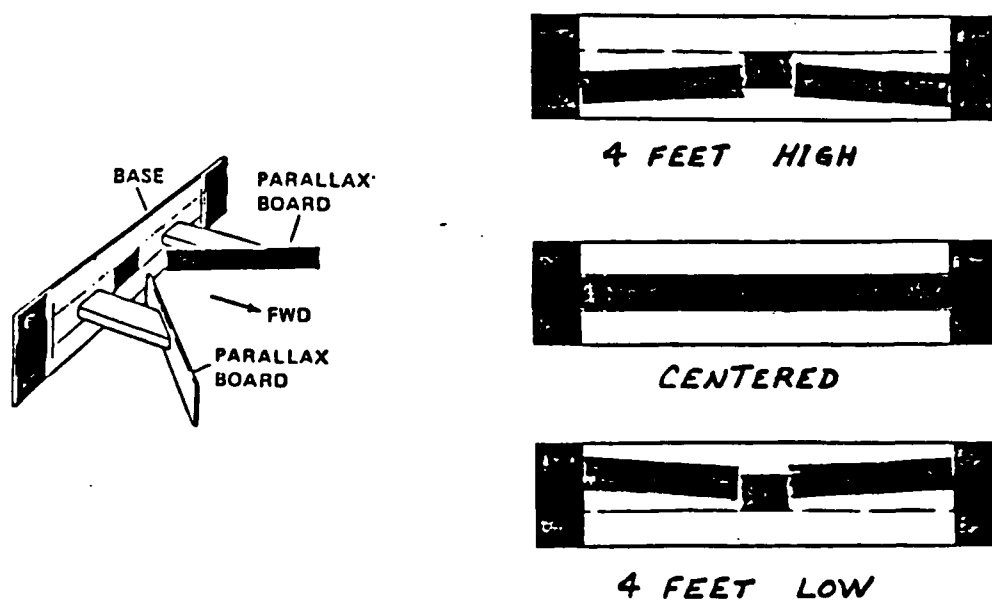


Figure 8. Details of HOVR Boards

rotorcraft was 66 feet away from the board (initial condition for this simulation), a vertical displacement of four feet relative to the center of the HOVR board resulted in the parallax board covering exactly half of the upper portion of the base. The position of the rectangle in the center of the base relative to the parallax boards provided a yaw cue to the pilot. Two towers were used in this simulation: one directly in front of the helicopter and one 45 degrees to the left of centerline to provide an additional fore-aft cue to the pilot. A top-view of the two hover test-rig towers is shown in Figure 9.

## 6. Data Acquisition

### a. Realtime Variable Recording and Strip Charts

All data (78 variables) were recorded digitally by a computer then converted to analog form and recorded on a magnetic tape. In addition three strip charts recorded an analog readout of 48 variables during the simulation. The strip charts were used extensively as a quick reference and to validate dynamic checks of the rotorcraft model.

### b. Pilot Remarks

Pilot remarks were encouraged at any time during the simulation and requested after each run. The commentaries were to include Cooper-Harper pilot ratings of the tasks. A voice-activated tape recorder was used to record the pilot commentary. The

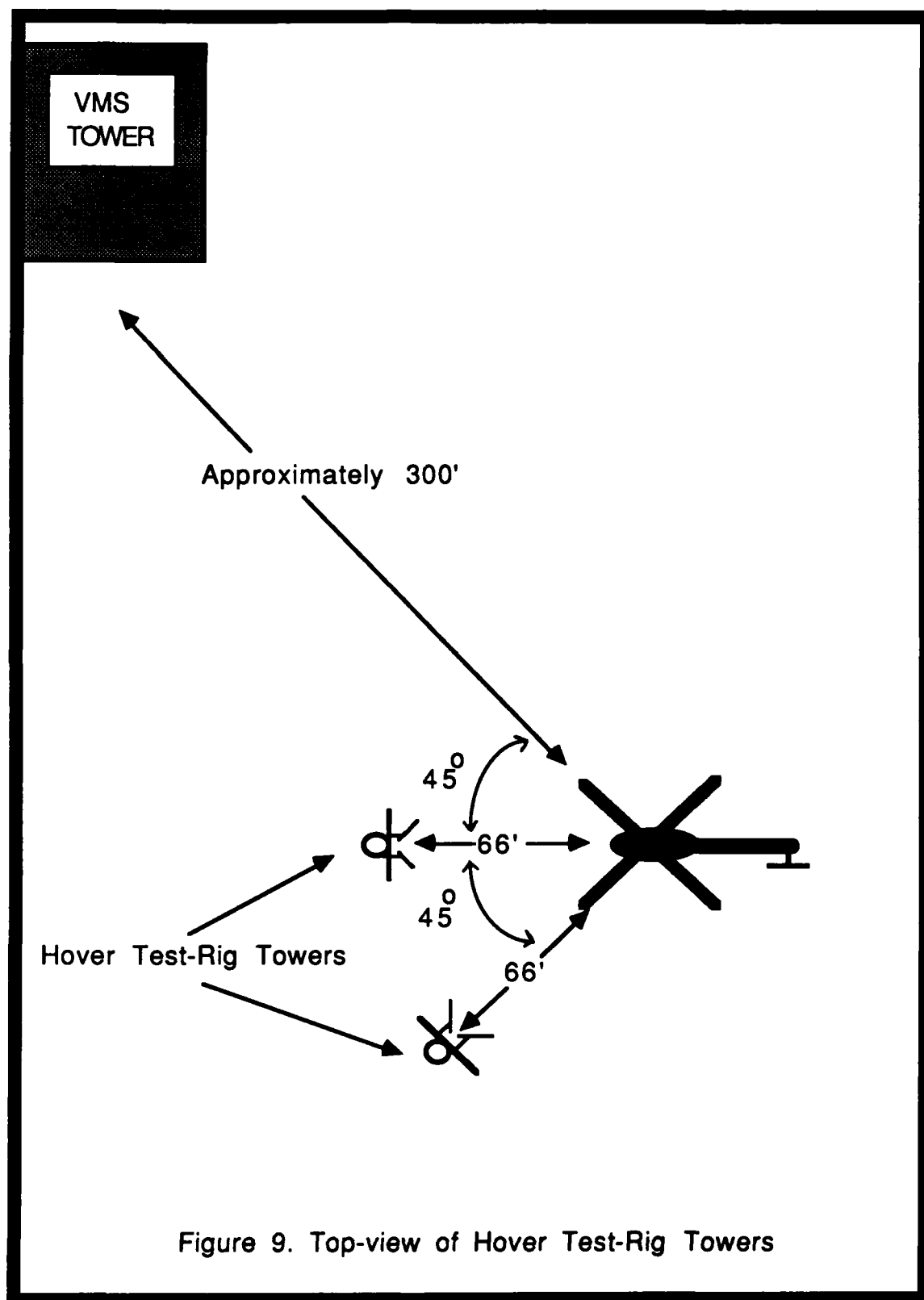


Figure 9. Top-view of Hover Test-Rig Towers

information on the cassette tapes was later transcribed to document form for ease of analysis.

c. Video Tapes

Video recordings of each run included the pilot's view of the task with HUD data superimposed on the screen.

d. Run Logs

Values of the variables and corresponding Cooper-Harper ratings were recorded in run logs at the engineers station in the control room. The run logs provided a quick, rough record of the pertinent data collected during the simulation.

7. Pilots

Four test pilots participated in the simulation: one pilot from Systems Technology, one from the Ames Research Center, and two from the Army Engineering Flight Activity (AEFA). This variation of flying backgrounds provided a unbiased data base of handling-qualities ratings. It was required that all participating pilots be test pilot rated. Each of the four pilots provided insights that were valuable in refining the simulation procedures.

## IV. EXPERIMENTAL PROCEDURE

### A. OVERVIEW

The recent flight tests conducted on the Canadian National Research Councils (NRC) variable stability helicopter led to the presumption that torque response could be used as measure of characterizing vertical axis handling qualities of rotorcraft. The objective of this simulation was to provide supporting data to the limited NRC experiment and expand upon the configurations investigated. For this simulation a wide range of torque dynamics were investigated for two individual tasks: a small-amplitude but precise timed bob-up/bob-down maneuver and a large-amplitude maximum rate of climb maneuver.

### B. PILOT PREPARATION

Pilots were given a standard briefing by the project engineer which included the simulation objectives, a short tour of the facility, and a cockpit checkout. Prior to the evaluations the pilots flew the simulator for a short time to gain familiarity with the aircraft model, visual scene, and displays. The evaluation began once the pilot felt he was comfortable with the simulator and the tasks. A Cooper-Harper rating flow chart similar to the one shown in Figure 3 was provided in the cockpit for the pilots to refer to at the conclusion of each run. Using the flow chart, the pilots would follow the decision



tree and come up with a rating they felt would best reflect the handling qualities they experienced on that run.

### C. THE BOB-UP/BOB-DOWN MANEUVER

A task was desired in which the pilot had to closely monitor the torque and regulate his control (collective) input to avoid damaging the rotorcraft. The bob-up task was chosen for four reasons:

1. It was primarily a vertical axis maneuver.
2. It had been studied in previous simulations conducted at the Ames Research Center.
3. It was a common military combat maneuver that is familiar to Army and Marine Corps pilots.
4. Because the maneuver demanded a lot of power, it required a close monitoring of torque.

The bob up task simulated a combat rotorcraft initially in a low hover (i.e. behind a tree or ridgeline); then rapidly climbing a small distance and stabilizing for a couple of seconds (i.e. launching a missile, getting a position fix); then descending quickly and stabilizing at the lower hover.

For this simulation the pilot initially began in a stable 15 foot hover, 66 feet from the forward hover board tower (Figure 7). The additional tower that was offset 45 degrees to the left of centerline assisted the pilot in maintaining the 66-foot range. The first part of

a run consisted of three bob-up/bob-down maneuvers, each performed in a specified amount of time. A study by Blanken and Whalley (Ref. 8) concluded that:

"When a time constraint is placed on the bob-up maneuver, pilots tend to fly the task at a common level of aggression for each configuration. There is a certain time limit for each configuration below which the pilot ratings begin to degrade. When a pilot is asked to fly the bob-up maneuver as aggressively as possible with no time constraint, he will tend to fly at a pace somewhat slower than he is actually capable of."

The optimum time for this task was calculated to be 9 seconds.

#### D. THE MAXIMUM RATE OF CLIMB MANEUVER

After the first day of recording data it was observed that much of the frequency characteristics of the torque response was camouflaged, due to the bob-up/bob-down task being a small-amplitude maneuver with rapid collective changes. If the frequency by which the pilot added and subtracted power was high, a low frequency torque response became "hidden". Therefore the max rate of climb maneuver was included in the simulation to reveal the influence of the frequency of the torque response on the pilot ratings.

#### E. OVERALL TASK OUTLINE

Details of the task are described as follows:

1. Pilot attained a stable 15-foot hover, level with the bottom HOVR board, 66 feet from the forward hover tower.

2. The controller started a timer which sounded a tone every 9 seconds for a total of 6 times.

3. Upon hearing the first tone the pilot would "pull-in" power and climb to next HOVR board, stabilize, call the word 'stable', and wait for the next tone.

4. After hearing the second tone he would descend back to the lower HOVR board, stabilize, and again call 'stable'. This continued for two more cycles or four more 'tones'. If the pilot could not get the rotorcraft stable by the time the tone sounded he was to proceed to the next HOVR board.

5. The maximum rate of climb maneuver immediately followed the bob-up/bob-down maneuver. After the third cycle the pilot did a small pedal turn to the right, established a visual reference on a distant tall object (in this case a computer drawn image of the Vertical Motion Tower). The pilot smoothly "pulled-in" power to the maximum (red line) torque and "climbed" the 200 foot tower. After stabilizing at the top he called 'stable', then descended back to the 15 foot HOVR board and established his final hover. The hover tower

was too close to the rotorcraft to provide the adequate depth perception and therefore could not be used during the max rate of climb maneuver.

6. At the completion of the max rate of climb maneuver the pilot went back to the initial condition (IC) and gave brief comments on the torque gauge response. The comments included a separate Cooper-Harper rating for both the bob-up/bob-down and max rate of climb maneuver. This concluded one run.

#### F. PILOT RATINGS

For good flying qualities the pilot desires to apply maximum power in a simple, deliberate, and predictable manner with minimal workload. Desired performance was achieved if the height error and vertical speed were nearly zero (or reversed) prior to the sounding of the next tone. Adequate performance was achieved if the vertical speed was converging towards zero and under positive control prior to the sounding of the next tone.

#### G. THRUST TO WEIGHT RATIO

The thrust to weight ratio (T/W) was set at an optimum of 1.1. If the T/W was less than 1.1 the rotorcraft would be unable to achieve the minimum vertical rate of climb in order to complete the maneuvers. If the T/W ratio was much higher than 1.1 the pilot would have plenty of excess power, the torque would fluctuate at the

bottom of the 'green' (normal) range, and therefore the pilot would fly the rotorcraft with "reckless abandon", disregarding the torque gauge. The torque limits were indicated by a red band on the cockpit gauge, a marker on the HUD torque tape gauge, and an audio warning tone to the pilot whenever the torque limit was exceeded.

## V. RESULTS AND ANALYSIS

### A. GENERAL

Approximately 180 runs of 80 torque response configurations were completed by the four test pilots. The three primary variables of the torque model transfer function,  $T_q$ ,  $\xi$ , and  $\omega$ , shown in Figure 4, were investigated in this simulation.  $T_q$  varied from 0 to 4,  $\xi$  from .1 to 1.0, and  $\omega$  from .25 to 10. Pilot evaluation data in the form of both Cooper-Harper pilot ratings and pilot commentary were recorded for each data run.

### B. DATA REDUCTION

After all of the runs were completed the entire data base was sorted and grouped by 1) Cooper-Harper Levels (1,2 or 3), 2) Task (bob-up/bob down or max rate of climb maneuver), and 3) Pilot. This meant that each of the four pilots had six groups of data:

- 1) Level 1 handling qualities, bob-up/bob-down maneuver
- 2) Level 2 handling qualities, bob-up/bob-down maneuver
- 3) Level 3 handling qualities, bob-up/bob-down maneuver
- 4) Level 1 handling qualities, max rate of climb maneuver
- 5) Level 2 handling qualities, max rate of climb maneuver
- 6) Level 3 handling qualities, max rate of climb maneuver

Once the data were grouped into these six categories, the torque response values of each category were fed into the computer program MATLAB. MATLAB is an advanced integrated spreadsheet

and graphics program which is commercially available. By applying a unit collective step input to each torque response, MATLAB produced time history plots. The three torque response time history plots of the bob-up/bob-down maneuver for pilot D are illustrated in Figures 10-12. The three torque response time history plots of the max rate of climb maneuver for pilot D are illustrated in Figures 13-15.

### C. BOB-UP/BOB-DOWN DATA ANALYSIS

By analyzing the torque response time history plots of each handling qualities level it was apparent that pilot ratings decreased with increasing overshoot. After plotting the family of curves for each level an overshoot boundary was created by drawing a line tangent to the points of maximum torque. The overshoot ratio ( $Q_0/Q_1$ ) is defined as the ratio of maximum torque to steady state torque. A composite graph of overshoot ratio versus time is illustrated in Figure 16(a) and depicts each of the three level boundaries. The initial downward slope of the two curves in Figure 16(a) marks the boundaries for overshoot. Peak time ( $t_p$ ) is defined as the time to maximum torque. The procedure for determining peak time ( $t_p$ ) is outlined in Figure 16(b). The pilots also preferred higher damped torque dynamics over lower damped responses. The horizontal sections of the two curves are the damping ratio boundaries. The damping ratio boundaries were calculated the same way as the overshoot boundaries.

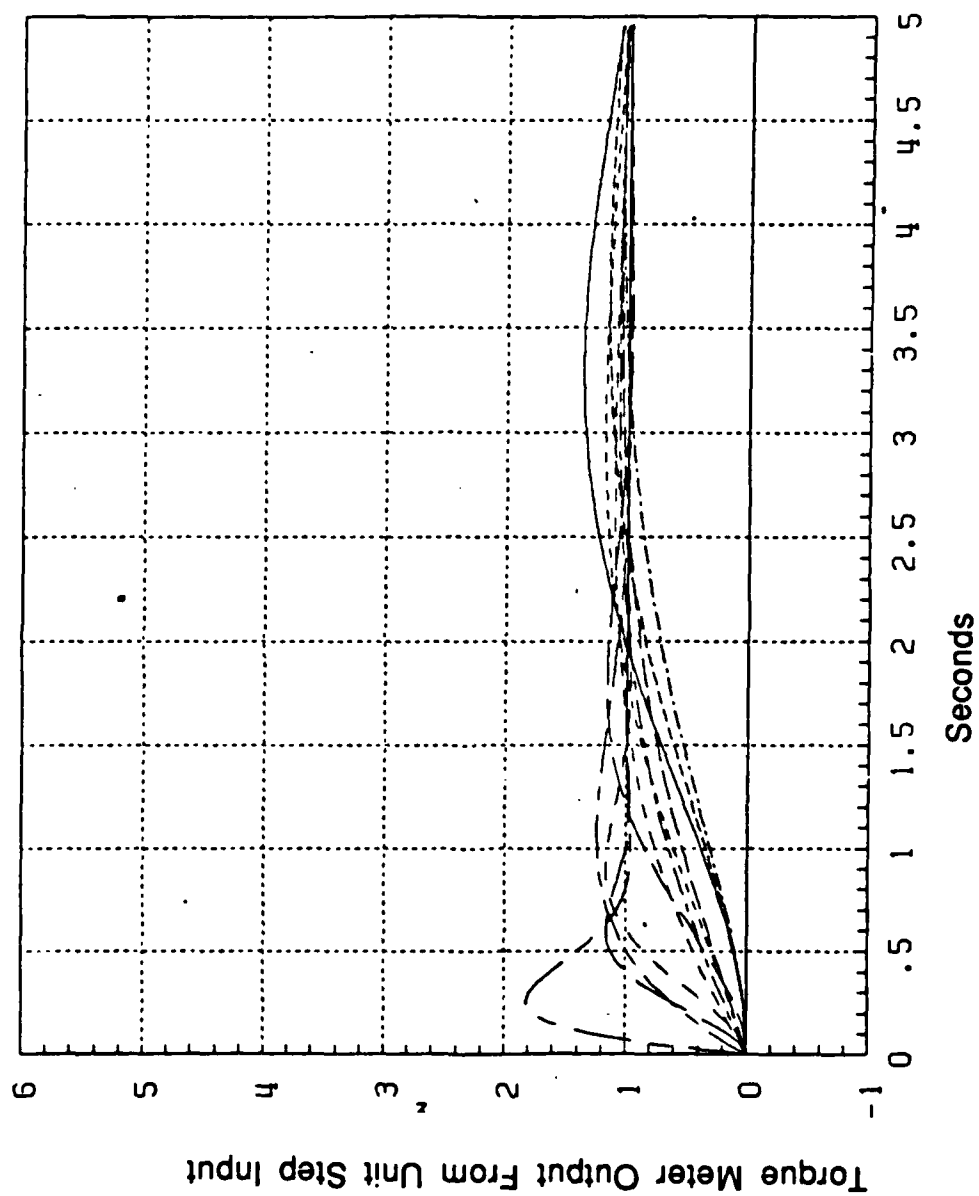


Figure 10. Level 1 torque responses, bob-up/bob-down maneuver



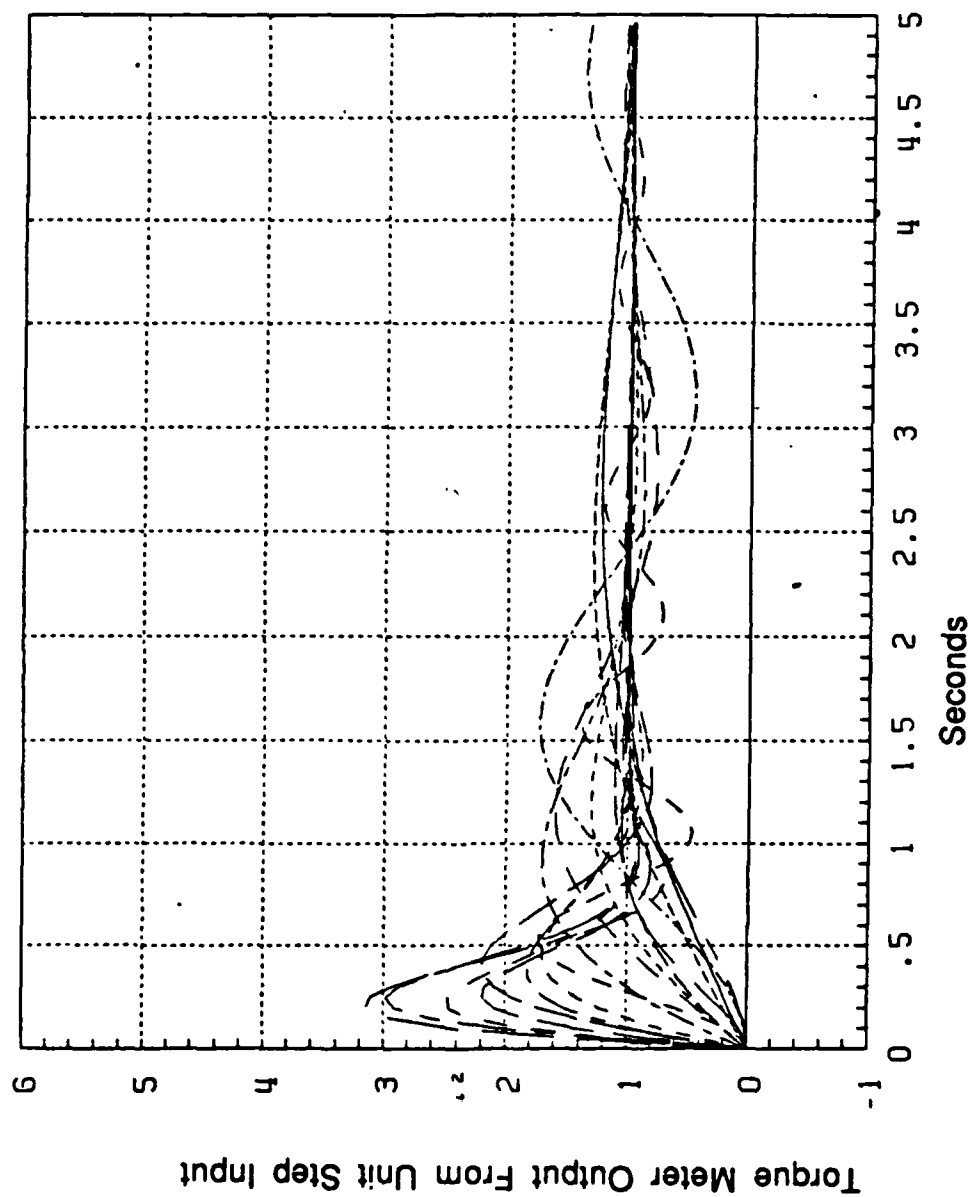


Figure 11. Level 2 torque responses, bob-up/bob-down maneuver

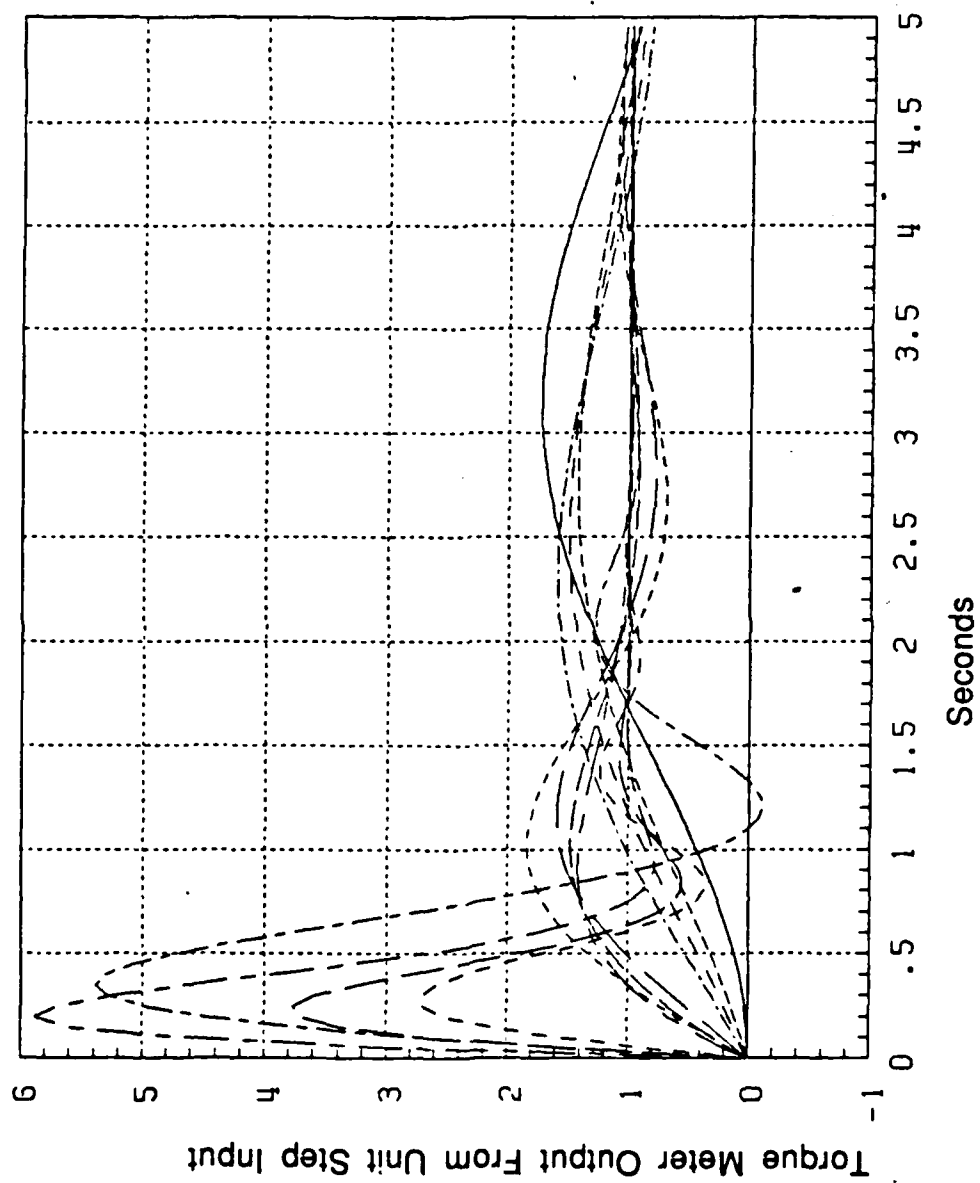


Figure 12. Level 3 torque responses, bob-up/bob-down maneuver

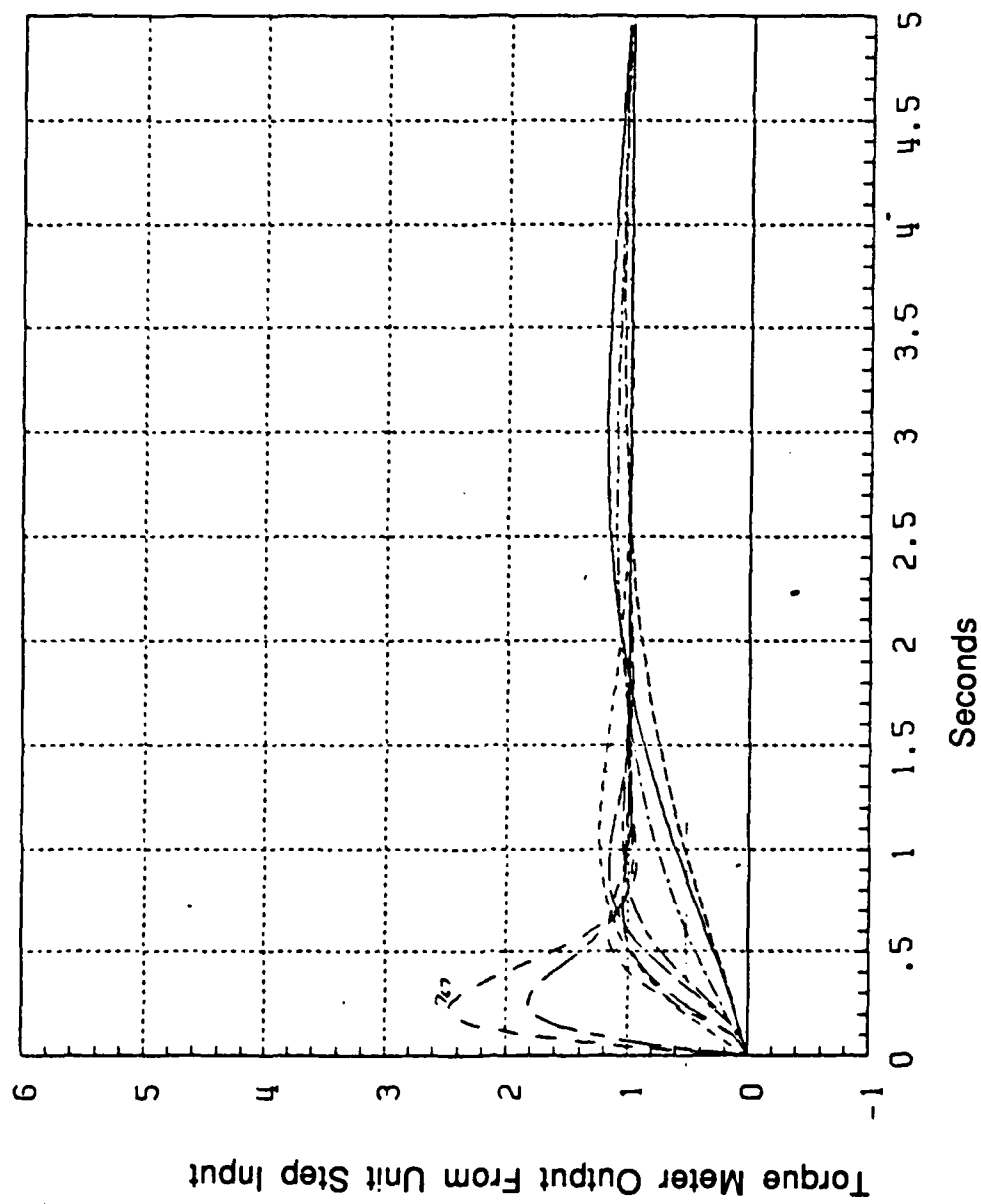


Figure 13. Level 1 torque responses, max rate of climb maneuver

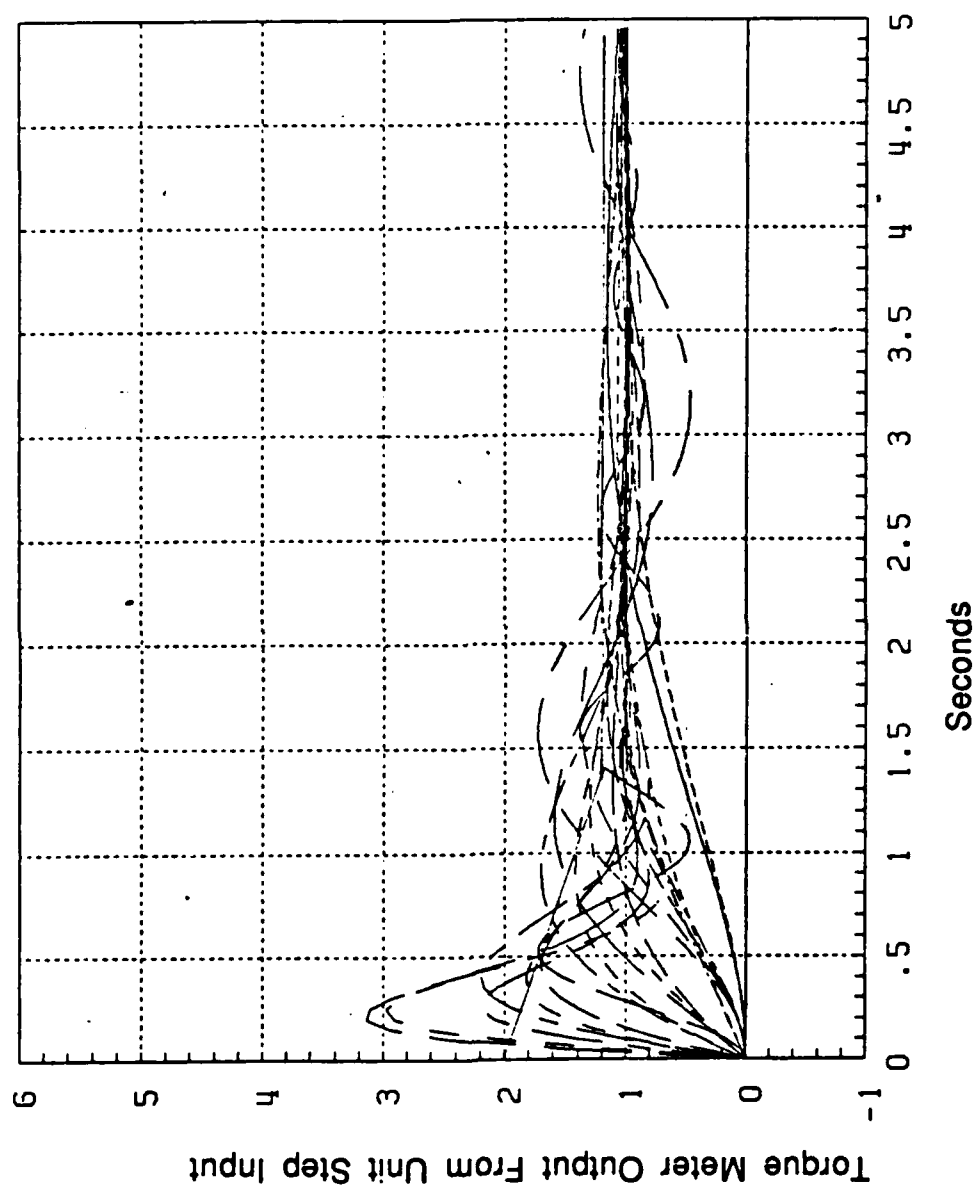


Figure 14. Level 2 torque responses, max rate of climb maneuver

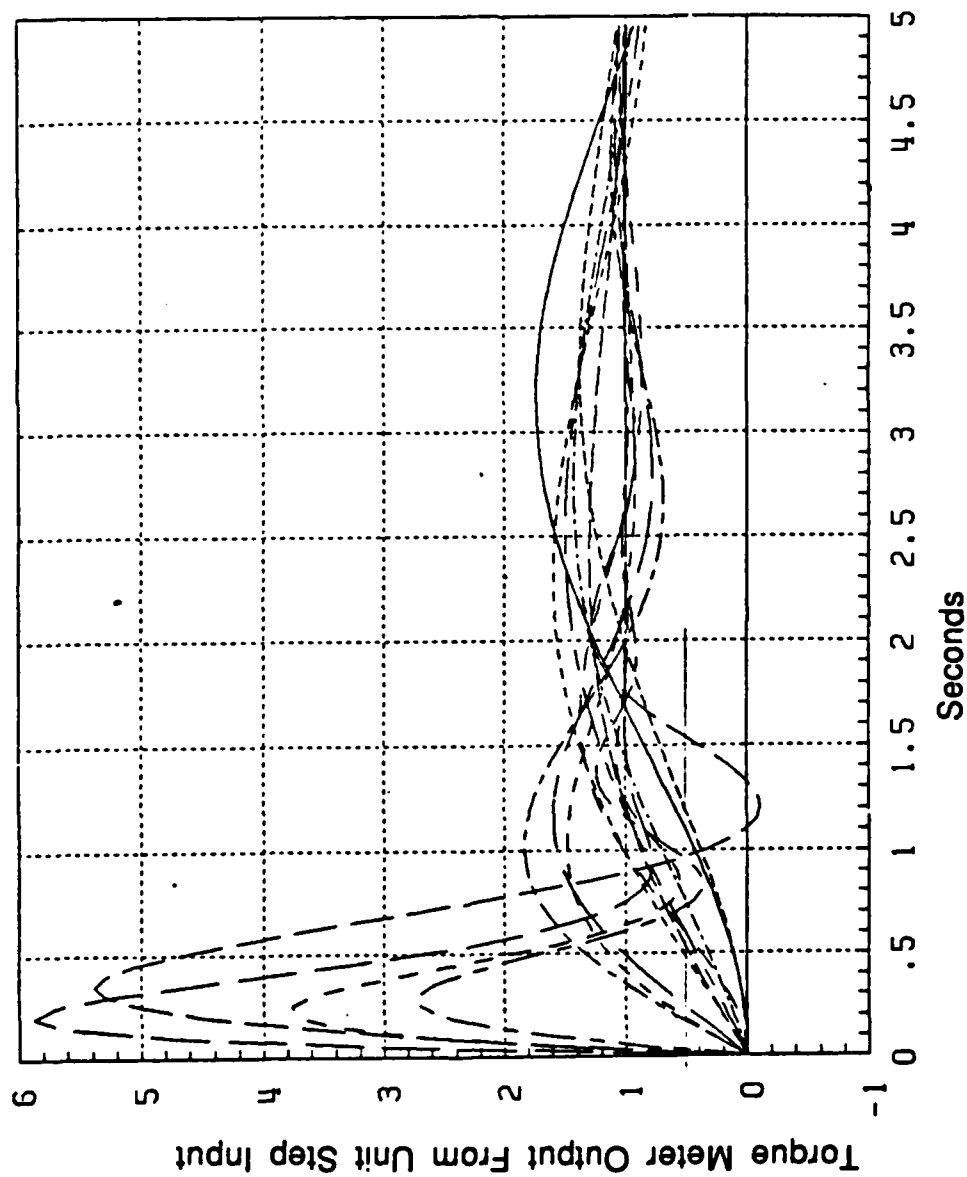
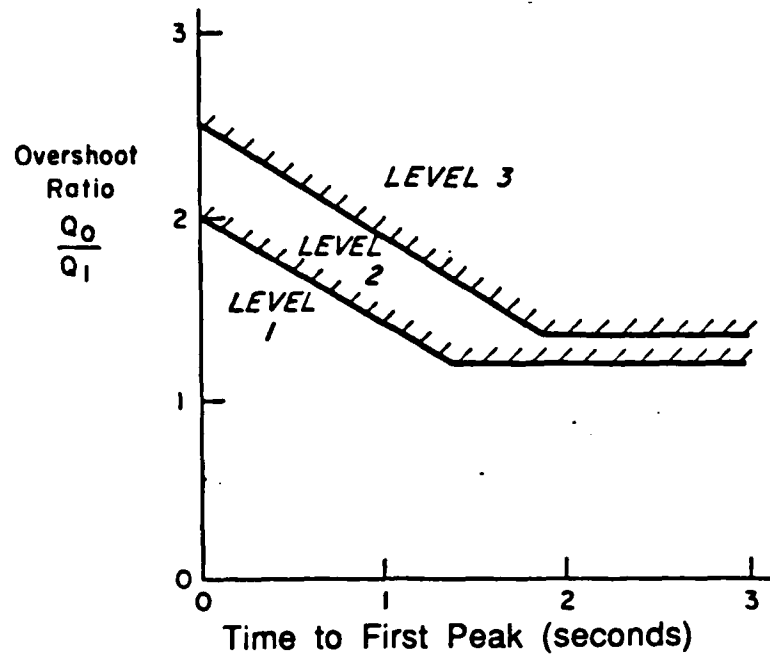
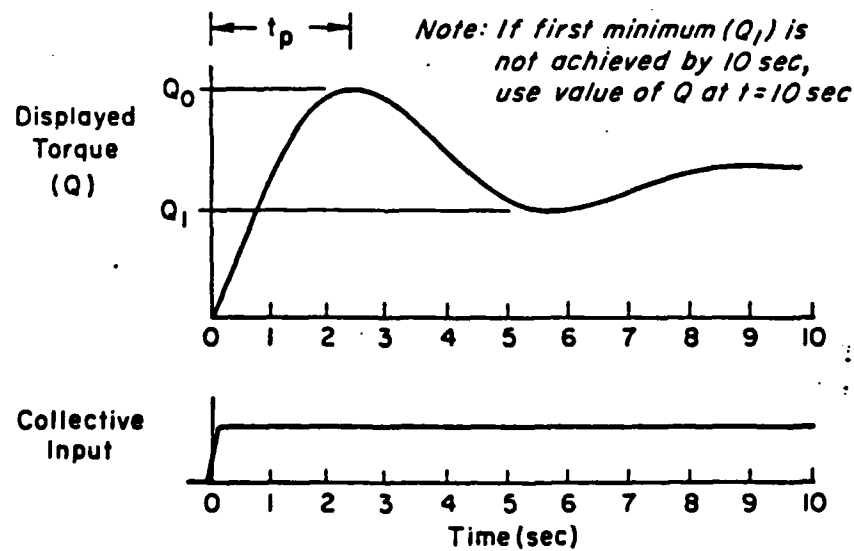


Figure 15. Level 3 torque responses, max rate of climb maneuver



a) Requirement on Dynamics of Displayed Torque Based on Step Collective Change



b) Definition of  $Q_0/Q_1$  and  $t_p$  for Displayed Torque Requirement

Figure 16. Displayed Torque Response Requirement (Ref. 11)

#### D. MAX RATE OF CLIMB MANEUVER DATA ANALYSIS

Figures 13-15 show the effects of low frequency torque response; as the frequency of the torque response decreased the pilot ratings decreased. In the max rate of climb maneuver the pilots were required to maintain a lot of torque for a longer period of time. Low frequency responses were sluggish and caused the torque to overshoot its maximum limit, a very unpredictable and undesirable characteristic. Frequency correlates as to how fast it takes a response to reach a certain percent of its steady state value. For these results 50% of the steady state value was used as the measuring point. If the torque response reached 50% of its steady state value in 1 second or less the pilots rated the response as Level 1. If the response took between 1 and 1.5 seconds to reach 50% of its steady state the pilots gave it a Level 2 response. Response times greater 1.5 seconds proved to be Level 3. The proposed 8501 revision has been updated to include the requirement of maximum time to 50% of the steady state value.

## VI. CONCLUSIONS

Results from the extensive data recorded during this experiment show a correlation between pilot opinion and the amount of torque overshoot and damping. Overshoots of less than 100% and damping ratios of 0.5 or greater were required for Level 1 handling qualities. These results concur with the limited in-flight test results collected at the National Research Council in Ottawa, Canada and expand upon the configurations investigated. In addition, for the maximum rate of climb maneuver, pilots tended to degrade the handling qualities ratings if the torque response was sluggish (low frequency). It was found that torque must reach 50% of its steady state value within 1 second for the response to have a Level 1 handling quality. The results of this experiment have caused a revision to the initial torque dynamic response requirements which did not address the characteristic of frequency.



## VII. RECOMMENDATIONS

It is recommended that the torque response data recorded in the simulator be verified in flight utilizing the NASA Ames AH-1, UH-1, and CH-47 helicopters. The simplest and most cost effective way of doing this would be to:

- 1) Attach a digital clock to the panel near the torque gauge.
- 2) Mount a video camera in the cockpit to record the torque gauge response and the digital clock readout.
- 3) Have the pilot perform a build up of collective steps up to the torque limit.
- 4) Re-construct a time history of the torque response by analyzing the video tape frame by frame.

This in-flight experiment would not only add validity to the new displayed torque response requirements of the 8501A revision, but would also document the torque response dynamics of three operational military rotorcraft.

## APPENDIX

### TIME DELAY

#### INTRODUCTION

A separate portion of this study was to determine the effects of time delay on rotorcraft vertical axis handling qualities. Digital components of flight controls systems create time delays. When the components are connected in series the time delays are added together to produce an overall time delay for the entire flight control system. With rapidly increasing need for digital flight controls in tomorrow's helicopters, there is an important desire to determine the effects of time delay in the vertical axis. The currently proposed vertical time delay requirements are largely based upon jet-lift VTOL-type response characteristics. The purpose of this study was to provide supporting data for rotorcraft-type responses. An initial study of the effects of time delay was performed in the fixed base simulator. Motion is an important factor to consider when observing time delay characteristics. Although this initial look at time delay was performed in the fixed-base simulator, it helped to localize the range of delay to be investigated in the actual in-flight tests.

#### FIXED-BASE SIMULATION

The experimental set-up for this portion of the study was practically identical to the simulation on torque response characteristics addressed previously in Chapter III. The delay

transfer function shown in the schematic in Figure 4 provided the necessary lag of collective inputs to response. Delay varied from 0 to .7 seconds. Current operational helicopters have time delays of approximately .2-.4 seconds. The pilots performed both the bob-up/bob-down and max rate of climb maneuvers for each run. For this study a overall Cooper-Harper rating was given for the combine runs instead of separately as in the torque response simulation. It was found that time delay increased nearly linearly with pilot ratings. For Level 1 handling characteristics the time delay was required to be below 0.2 seconds. A plot of Cooper-Harper rating versus time delay is illustrated on Figure 17.

#### IN-FLIGHT TESTING

A more appropriate evaluation of time delay was investigated in the NASA-Ames CH-47B variable stability helicopter. For ease of testing, the 15-foot interval bob-up/bob-down maneuver and the max rate of climb maneuver was combined into one 40-foot bob-up/bob-down maneuver. As in the previous study, each run consisted of three bob-ups and three bob-downs. At the completion of each run the pilot gave a brief commentary on the handling qualities which included a Cooper-Harper rating. Just as in the simulator, in-flight time delays proved to increase nearly linearly with pilot ratings. In flight, time delays could be as high as 0.4 seconds and still remain Level 1. A plot of in-flight ratings versus time delay are superimposed on the simulation plot in Figure 17.

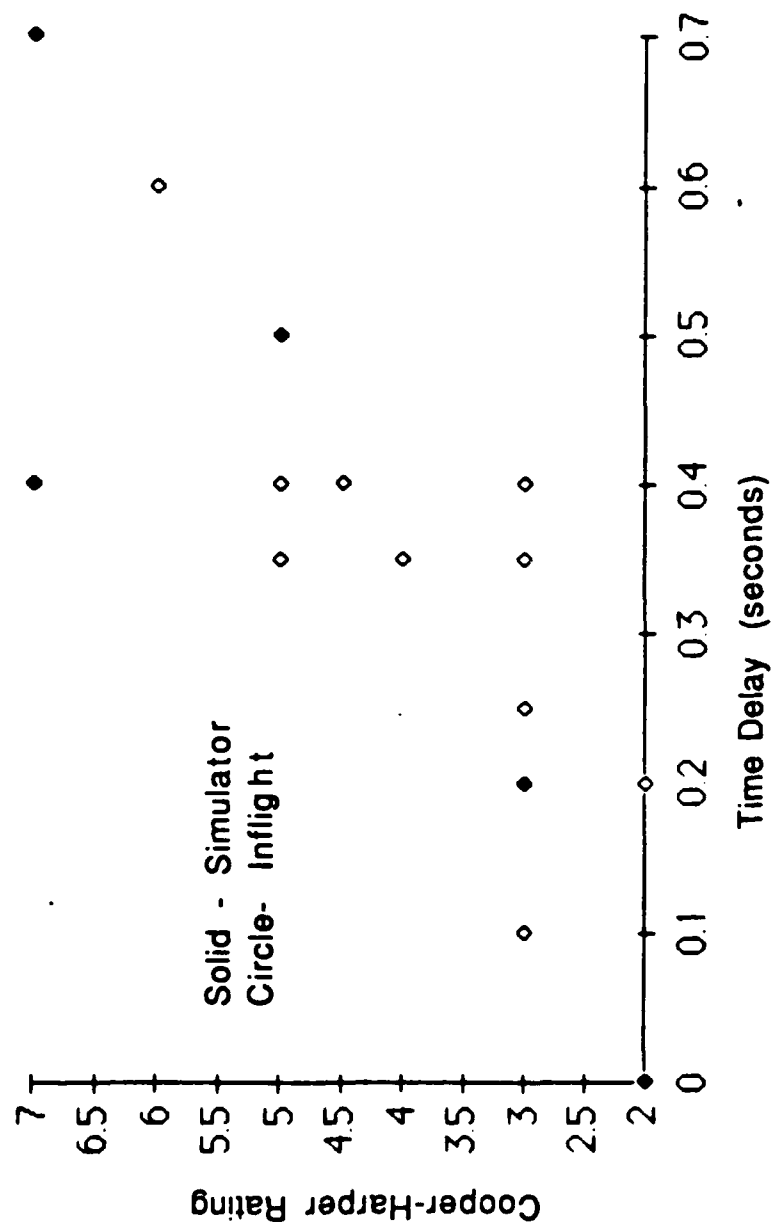


Figure 17. Cooper-Harper Rating vs. Time Delay, Inflight and Fixed Base

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